PERFORMANCE OF DIELECTRIC PROPERTIES DUE TO THE PRESENCE OF MOISTURE IN VEGETABLE INSULATION OILS AND KRAFT PAPER IMMERSED IN THE OILS

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This research is dedicated to my beloved wife and son, Amina and Suleiman-Abba and my beloved sister-in-law Aisha Raji.

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ABSTRAK

Minyak penebat sayur-sayuran dalam pengubah telah menjadi kenyataan. Walau bagaimanapun, mereka sememangnya hidrofilik dan boleh menyerap banyak kelembapan. Kewujudan kelembapan dalam penebat pengubah umumnya akan menurunkan voltan pecahan (BDV) minyak. Kelembapan juga akan mempercepatkan kemerosotan selulosa dengan meningkatkan kekonduksian arus terus (DC) itu. Kedua-dua minyak dan selulosa adalah komponen sistem penebat pengubah. Terdapat beberapa kajian yang telah dilakukan oleh penyelidik lain pada minyak berasaskan sawit tetapi mereka tidak menangani kesan peningkatan kelembapan dalam jenis minyak tidak pula memberi kefahaman kemerosotan selulosa apabila direndam dalam minyak. Oleh itu, adalah penting untuk memahami bagaimana kelas minyak ini mengekalkan kekuatan dielektriknya dan hubungannya dengan kertas kraft selepas menyerap begitu banyak kelembapan. Dalam kajian ini, Jelmaan Fourier Inframerah (FTIR) spektroskopi, analisis pentitratan Karl Fischer, Standard ujian dielektrik IEC dan teknik penilaian penebat Arus Polarisasi dan Depolarisasi (PDC) yang dibina telah digunakan untuk mengkaji peningkatan kelembapan dalam empat minyak berasaskan sayuran dan kertas kraft yang tenggelam dalam mereka. Minyak yang dikaji ialah tiga minyak berasaskan sawit, minyak Minyak Sawit Merah (RPO), Ester Asid Lemak Sawit (PFAE) dan Ditapis Bleached Deodorized Minyak Sawit (RBDPO) dan berasaskan kacang soya Envirotemp® FR3™. Kelembapan telah diubah oleh sehingga 0.3% (mengikut isipadu) dan sampel selulosa adalah 0.2mm, 0.5mm dan 1mm tebal. Hasil daripada kajian ini menunjukkan bahawa hidrolisis sampel minyak ini menyebabkan tahap kelembapan mereka meningkat sebanyak 100% kepada 700%. Di samping itu, peningkatan kelembapan menyebabkan perubahan berlaku dalam struktur asid lemak minyak penebat berasaskan sawit sahaja dan tidak kepada minyak berasaskan kacang soya. Membandingkan BDV jenis minyak ini dengan IEC 60156 Standard 30kV, kajian ini telah mendapati bahawa FR3, PFAE dan RBDPO mampu kekal di atas standard di tahap kelembapan masing-masing pada 0.055%, 0.025% dan 0.015% manakala BDV dalam RPO adalah di bawah piawaian. Persamaan untuk menganggarkan BDV minyak sayuran daripada kandungan kelembapan juga telah dibangunkan. Anggaran BDV bagi sampel minyak kebanyakannya diubah di antara 1 hingga 20% daripada eksperimen BDV. Kajian ini juga mendapati bahawa apabila kelembapan dalam minyak meningkat, sampel kertas kraft menyerap minyak dan kelembapan hilang kepada minyak. Penyerapan minyak juga adalah fungsi ketebalan kertas dan kelembapan dalam minyak. Kekonduksian kraft sampel kertas yang tenggelam dalam jenis minyak didapati mempunyai nilai terendah di tahap kelembapan minyak sebanyak 0.01% untuk kedua-dua RPO dan PFAE dan 0.02% untuk kedua-dua RBDPO dan FR3. Oleh itu untuk prestasi penuaan yang lebih baik, kajian ini menyimpulkan bahawa minyak penebat sayur-sayuran tidak boleh menjadi kering seperti minyak mineral kerana selulosa mempunyai kekonduksian yang lebih rendah dalam minyak sayur-sayuran lebih lembap.

ABSTRACT

Vegetable insulation oils in transformers have become a reality. However, they are inherently hydrophilic and can absorb much moisture. Existence of moisture in transformer insulation will generally lower the breakdown voltage (BDV) of oil. Moisture will also accelerate cellulose deterioration by increasing its Direct Current (DC) conductivity. Both oil and cellulose are components of the transformer insulation system. There are few studies that have been done by other researchers on palm-based oils but they neither address the effect of increasing moisture in the oil types nor do they give understanding of the deterioration of cellulose when immersed in the oil. It is therefore important to understand how these classes of oils retain its dielectric strength and its relationship with kraft paper after absorbing so much moisture. In this study, Fourier Transform Infrared (FTIR) spectroscopy, Karl Fischer titration analysis, IEC dielectric test Standards and established Polarization and Depolarization Current (PDC) insulation assessment technique were used to study moisture increase in four vegetable-based oils and kraft paper immersed in them. The oils studied were three palm-based oils, Red Palm Oil (RPO), Palm Fatty Acid Ester (PFAE) and Refined Bleached Deodorized Palm Oil (RBDPO) and one soybean-based Envirotemp® FR3™. Moisture was varied by up to 0.3% (by volume) and the cellulose samples are of 0.2mm, 0.5mm and 1mm thickness. Results from these studies show that the hydrolysis of these oil samples causes their moisture level to increase by 100% to 700%. In addition, the moisture increase causes changes in the fatty acid structure of the palm-based insulation oil only and not on the soybean-based oil. Comparing the BDV of these oil types to IEC 60156 standard of 30kV, this study found that FR3, PFAE and RBDPO are capable of remaining above standard at moisture level up to 0.055%, 0.025% and 0.015% respectively while the BDV in RPO was below standard. An equation to estimate the BDVs of vegetable oils from their moisture content was also developed. The estimated BDVs of the oil samples mostly varied between 1 to 20% from the experimental BDVs. The study also found that as moisture in the oil increases, kraft paper samples absorb oil and lose moisture to oil. The oil absorption was also a function of paper thickness and moisture in the oil. The conductivity of kraft paper samples immersed in oil types were found to have lowest values at oil moisture level of 0.01% for both RPO and PFAE and 0.02% for both RBDPO and FR3. Thus, for better aging performance, the research concludes that vegetable insulation oils should not be as dry as mineral oils as cellulose has lower conductivity in wetter vegetable oil.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ASTM	-	American Society for Testing and Materials
BDV	-	Breakdown Voltage
BS	-	British Standard
CCO	-	Crude Coconut Oil
CPKO	-	Crude Palm Kernel Oil
DC	-	Direct Current
DGA	-	Dissolved Gas Analysis
FDS	-	Frequency Domain Spectroscopy
FESEM	-	Field Emission Electron Microscope
FR3	-	Envirotemp FR3
FTIR	-	Fourier Transform Infrared
GUI	-	Graphic User Inter Phase
HMWH	-	High Molecular Weight Hydrocarbon
HVDC	-	High Voltage Direct Current
IEC	-	International Electrotechnical Commission
IEEE	-	Institute of Electrical and Electronics Engineers
IR	-	Infrared
KF	-	Karl Fischer
KP	-	Kraft Paper
KP1	-	Kraft Paper 1 (0.2 mm thick)
KP2	-	Kraft Paper 2 (0.5 mm thick)
KP3	-	Kraft Paper 3 (1.0 mm thick)
LCR	-	Inductance, Capacitance and Resistance
MPOB	-	Malaysia Palm Oil Board
NPLC	-	Number of Power Line Cycles
PCB	-	Polychlorinated Biphenyls
PDC	-	Polarization and Depolarization Current
PFAE	-	Palm Fatty Acid Ester
ppm	-	Particles Per Million

PVC	-	Polyvinyl Chloride
RBDPO	-	Refined Bleached Deodorized Palm Oil
RPO	-	Red Palm Oil
RVM	-	Return Voltage Measurement
StdDev	-	Standard Deviation

LIST OF SYMBOLS

∂	-	Patial Differential
μ	-	Charge Mobility
σ	-	Conductivity
ϵ	-	Permittivity
ω	-	Frequency
δ	-	loss angle
π	-	Pi
λ	-	Wave Length
∇	-	Del Operator

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Power transformers are one of the few equipment in the power network that are placed within vicinity of residences, shopping centers, neighborhoods and offices. In these power transformers are millions of cubic liters of mineral oil used as liquid insulator and thus raising safety and environmental concern to governments and power utility companies [1, 2, 3, 4]. When accidents such as shown in Figure1.1 occurs, the environmental health and safety is at risk. Hence the need arises to seek alternative insulating oil that is environmentally friendly and meets all insulation oil performance criteria. This effort of seeking alternative insulation oil for power transformers became extensive in the early 1990s after transformer oil spills that resulted from tank ruptures after a truck collided into power transformers in Waverly, Iowa [5]. Furthermore, the natural disasters caused by hurricanes Katrina and Rita compelled the USA government to urgently seek alternative insulation oil for power utility equipment [6].

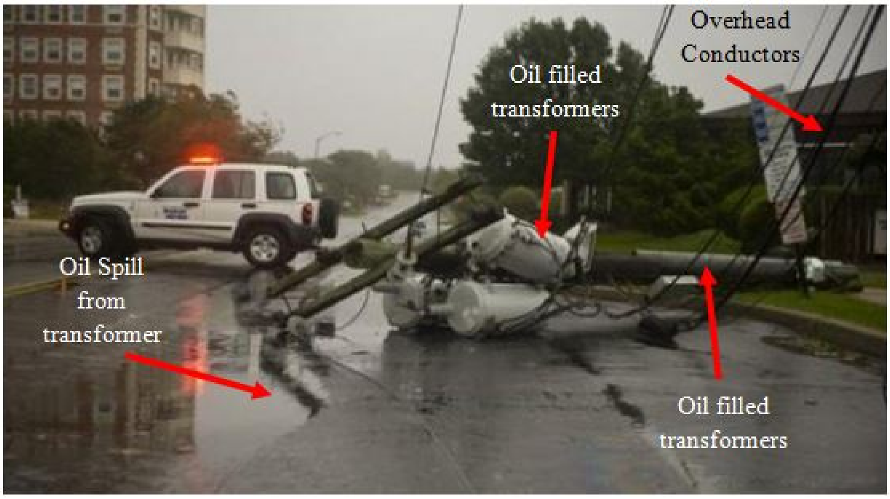

Figure 1.1: Pole mounted transformer tank raptured after hurricane Irene in New York

The success of these efforts manifested in the development and commercial use of EnviroTemp® FR3™ and BioTemp® biodegradable natural ester insulation oils, made from vegetable seed oil, as power transformer insulation oil. The commercial success of these two oils propelled other plant based oils like palm oil, castor oil and moringa olivera oil as potential insulation for power transformers and they are at various stages of development. Besides environmental and safety considerations, the biodegradable based insulation oils have been researched to guarantee long life cycle for transformers because they decrease the aging or deteriorating process of the kraft paper (solid insulation) [7, 8].

Temperature and moisture are the major factors that accelerate cellulose degradation and deterioration. This degradation of cellulose during operation is called depolymerization process which release moisture as one of its by-products [9, 10]. The presence of this moisture in the cellulose weakens its dielectric strength thus making it vulnerable to possible catastrophic failure [11]. For the purpose of service longevity, insulation oil should absorb moisture from cellulose so as to keep it dryer and consequently reduce its rate of depolymerization.

Natural ester oils have more affinity for moisture than mineral oils and so they have capability to absorb more moisture. This ability of natural esters to absorb and retain more moisture makes it possible to keep the cellulose in the transformer drier [1, 6]; thus slowing down the polymerization or degradation process. This process will increase the life cycle of the transformer [12]. Natural ester oils also have the added advantage of absorbing more heat and so they are more suitable in multiple-load break-switching operations compared to mineral oil insulation [3]; thus transformer size can be made smaller for the same power capacity [13].

Natural ester oils like FR3 and Biotemp have successfully been used in power transformers in some utility power system networks [1, 8, 14]. A lot of research efforts have been made into other plant based sources of insulation oil and including various grades of palm oil. Most of the researchers concluded that palm oil is a veritable alternative for power transformer insulation as it possesses good electrical properties considered as better than that of mineral oils [15, 16, 17, 18]. Palm Fatty Acid Ester (PFAE) is one of such oils that is presently used in Japan as insulating oils for distribution transformers [19].

However, the challenge of using natural ester oil (especially palm-based) in transformers is that not much is understood about the moisture behaviour of kraft paper

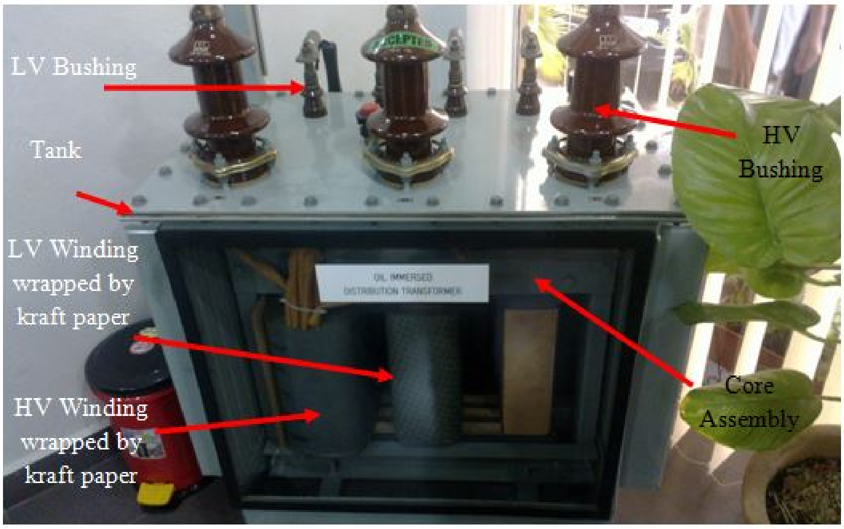

Figure 1.2: Model of oil filled distribution transformer

when it is immersed in palm oil based insulation oil when the moisture level varies. The importance of understanding how moisture in the vegetable oils will influence molecule hydrogen bonding behaviour motivated this research. Furthermore, the research studied the response of oil breakdown voltage (BDV) and dielectric current (DC) conductivity response of kraft paper when immersed in these oils.

1.2 Power Transformer Insulation System

Transformers are essential power system equipment that converts electrical energy from one voltage level into another by electromagnetic induction. It consists of primary and secondary windings, core assembly and insulators as shown in Figure 1.2. Current flowing through the conductors in the primary winding creates a magnetic flux in the core and the resulting magnetic field creates an induction current that flows in the conducting wires in the secondary winding. All conducting materials in transformers have to be perfectly insulated for the purpose of maintaining current floe on its desired path as well as insulating them from one another. Kraft paper is used to electrically separate these conducting paths and in oil filled power transformers, the whole assembly is immersed in oil. The oil has the dual function of being an insulation and a heat exchange medium.

1.2.1 Kraft Paper Insulation

The kraft paper is organic compound of polymer glucose units that has the general formula $[C_6H_{10}O_5]_n$. It is a strong paper that is made from wood pulp with very high concentration of cellulose and low lignin [20]. The paper is required to have low lignin because its hydrophobicity will cause the hydrogen bonds between cellulose fibers to weaken. The chemical structure and physical structure of cellulose polymer appear as flexible-like structure.

The kraft paper has certain distinct dielectric properties such as low conductivity, high dielectric breakdown strength and low dielectric loss. The advantages and disadvantages of the use of kraft paper in electrical equipment are listed in Table 1.1 [21].

Table 1.1: Advantages and disadvantages of kraft paper in electrical equipment [21]

No	Advantages	Disadvantage
1	Good dielectric properties	Excessive dielectric loss at high temperature/frequency
2	Good mechanical properties	High capacitance and permittivity (for thicker papers)
3	Chemically stable	
4	Low cost	
5	High dielectric strength	
6	Good impregnability	

Power transformers in utility networks have 30 years normal life span and many of them deteriorate faster when they start approaching 20.55 years of their life[22]. This has encouraged continuous studies of cellulose in oil-filled transformers because cellulose degradation is considered to be a major contributor to transformer aging [23]. Such studies include, but not limited to, the process of manufacturing of the kraft paper, the insulation oil used in the transformer (in which the paper is immersed) and how both paper and oil behave when they are in composite. Understanding the behaviour of the oil-paper insulation guides transformer designers to optimize usage of the kraft paper insulation in power transformers.

Since kraft paper has the property of having high dielectric loss and it is also hygroscopic [13], this study considers it important to investigate how increasing moisture level in vegetable oils influences these kraft paper characteristics.

1.2.2 Power Transformer Oil Insulation

The role and importance of insulation oil in power transformer can never be overemphasized as several million liters of insulation oil are used in most power transformers worldwide [19]. During operation, energy losses cause the generation of heat and thus insulation oil used in power transformer undergoes severe thermal and electrical stresses. So it is expected that insulation oil used in transformers must remain stable over a long period under such strenuous conditions. Besides being good insulators and heat exchangers, insulation oils also function as arc quenching and acoustic dampening media [24].

Generally, the performance of the insulation oil is affected by impurities like moisture, fibers and decomposed products of kraft paper [25]. Moisture is inherently polar so when insulation oil is under the influence of electrical field, the moisture increases flow of charged molecules causing electron avalanche [25]. Therefore, the presence of moisture in the insulation oil drastically impedes the ability of the oil to maintain stability during transformer operating conditions. Thermal oxidation and hydrolysis are common causes of insulation oil degradation, which in turn, changes the molecular structure of the oil. When these oils degrade, dielectric properties like breakdown voltage (BDV), viscosity, flash point and pour point that characterize the insulation oil are affected; thus making them vulnerable to faults like partial discharge, arcing or corona discharge. Insulation oil manufacturers have used additives such as polychlorinated biphenyls (PCBs) to minimize the oxidation of oils [24]. However, PCBs have been banned from use due to the hazards they cause on environment.

The common insulation oil used in power transformers so far is the petroleum based mineral oil but researchers and engineers are vigorously seeking and promoting alternative insulation oils like silicon, synthetic and natural ester oils. Natural ester oils like soybean based FR3 and sunflower based Biotemp have become very successful alternatives to mineral insulation oil in power transformers today. Some other vegetable insulation oils like PFAE have also been successfully used in distribution transformers in Japan [19]. Unlike mineral oils, natural ester oils are biodegradable oils obtained from readily available natural products and they are non toxic. They constitute of mainly triglycerides, alcohols and fatty acids.

1.3 Problem Background

Some common causes of power transformer failures include insulation failures, tap-changer failures and bushing failures. Earlier studies have shown that about 41.8 % of transformer failures are attributable to insulation failures [26, 27]. The main insulating materials in the power transformers are oil and kraft paper. The oil acts as both insulator as well as a heat exchange medium while the kraft paper is the solid insulation wrapped around conducting wire or between coils that have different voltage levels [26]. Either individually or in composite, both insulating materials play key roles in the rate of failure and aging of the transformer. Irrespective of their initial purity, during operation they will degrade and produce water as by-products of the degradation process [11, 28]. Cellulose paper degradation is more critical compared to the oil degradation because the polymerization process of paper is irreversible while the filtration and other oil treatment procedures can restore the insulation oil to a certain degree.

The solid and liquid components of the insulation system all contribute to the moisture that domiciles in the power transformer. The internal temperature rise accelerates the rate of cellulose degradation; thus also increasing rate of moisture by-products from cellulose. The ability of insulation oil to absorb the moisture from the cellulose keeps the paper dryer and will increase the service life of the transformer [12, 29, 30, 31]. Thus during its operation, the transformer insulation system (i.e. oil and cellulose paper) seek moisture equilibrium. The aging and deterioration process of the power transformer is therefore dependent on the type of oil insulation used and the moisture equilibrium it can maintain.

As a result of the resounding successful development of FR3 and Biotemp, many researchers started exploring the possibility of using other plant based oils, e.g. palm oil and its derivatives, as transformer insulation oils. Research have shown that Crude Palm Kernel Oil (CPKO), Crude Coconut Oil (CCO), Refined Coconut Oil (RCO), and Refined Bleached Deodorized Palm Oil (RBDPO) all have the electrical, chemical and physical potentials suitable for use as insulation oil [15, 17]. These oils have organic compounds that make them different in behaviour and character from the inorganic mineral oils [32].

The importance of studying kraft paper insulation behaviour when immersed in vegetable-based oils can never be over emphasized because it is the most important and easily degradable insulation material in the transformer. It is equally important to note that no matter how promising the properties of palm oil is as insulation oil, the understanding of its properties when it is in composite with the other insulation materials of the power transformer is critical to arriving at a conclusion on its use as insulation oil. There are a few studies that have been done on the effect of the moisture in vegetable or plant based insulation oil on kraft paper insulation when the paper is immersed in these oil types [16, 26, 30]. However, these previous researches did not consider how the inherent hygroscopic characteristic of vegetable-based oil and their ability to absorb large quantity of moisture affects the oil behaviour and its relationship with kraft paper in which it is immersed.

As palm-based insulation oils are gaining usage in power transformers, it is therefore imperative to study the characteristics of the cellulose paper immersed in these types of insulation oil with increasing moisture content. If these characteristics are understood, the suitability or otherwise of palm oil as alternative to mineral oil will be apparently conclusive. This is primarily because the dielectric properties of the cellulose are depending on its permittivity. The permittivity changes as moisture inside the oil changes; thus that will change the whole insulation property of the power transformer. Furthermore, load and atmospheric conditions can affect moisture inside the cellulose paper [33]. Thus studying the moisture equilibrium relationship between vegetable insulation oil and cellulose and how it affects their dielectric properties is important.

1.4 Transformer Insulation Assessment

The method of assessing transformer insulation depends on the insulation characteristic that is being investigated. When investigating fault types in power transformers, the dissolved gas analysis (DGA) assessment method can be used because the method utilizes dissolved gases in the oil to ascertain the insulation condition [34]. However, considering that moisture in kraft paper is critical in the determination of the service life of the transformer, the DGA assessment method will not be able to determine moisture state of the kraft paper.

The assessment of moisture in kraft paper is complex and cannot be measured directly. Many researchers have published many technical papers that show that kraft paper assessment is better done using dielectric response theory. Thus assessment methods like polarization and depolarization current (PDC), return voltage measurement (RVM) and frequency domain spectroscopy are used to assess transformer solid insulator [35, 36, 37, 38, 39]. These three assessment methods are based on dielectric relaxation method in solid insulators [40].

The dielectric relaxation in solids is stochastic and some experimental and mathematical tools are needed to explain the process. The experiment is based on the principle that all materials are liable to have increasing ionic movement whenever they are subjected to external electric field or thermal stress [41]. If the material contains more ionic molecules, the ionic movements will increase. The experimental process involves a time domain recovery of strain after the removal of a stress because the nature of the strain is dependent on the properties of the solid material. Thus the relaxation current is the strain that is caused by the applied electric field in the three aforementioned assessment methods used in solid insulation assessment [42].

In this study, kraft paper samples immersed in vegetable insulation oil (with changing moisture levels) are subjected to sustained DC voltage. The dielectric response polarization and depolarization current (PDC) measured is used to calculate the DC conductivity of the kraft paper samples.

1.5 Objective of Study

The primary objective of this research is to investigate how moisture increased in three palm-based and one soybean-based insulation oils affects their dielectric strengths and also how it affects the conductivity of the kraft paper insulation in which they were immersed in. A set of sub-objectives were developed and pursued with the target of achieving the primary objective. The study was done in laboratory conditions at constant temperature. The sub-objectives are

i To characterize the effect of moisture on the molecular structure of vegetable-based insulation oils,

ii To evaluate the effect of moisture increase on the dielectric strength of the insulation oils,

iii To develop a mathematical model that can be used to predict BDV using wetting characterization, iv To investigate the DC conductivity in kraft paper immersed in vegetable-based insulation oils,

v To investigate and characterize effect of vegetable-based insulation oil moisture level on kraft paper.

1.6 Scope and Limitation of Study

This research is a laboratory experiment and is limited to the following scope of study;

i Oil samples functional group response to moisture changes,

ii Dielectric strength response to moisture changes in oil samples,

iii Diffusion of oil and moisture in kraft paper immersed in the oil samples,

iv DC conductivity response of kraft paper immersed in oil samples,

Thus the research was limited to

iv Four (comprising three palm-based and one soybean-based) vegetable oil types,

vi Dielectric properties study is limited to BDV insulation test for oils and DC conductivity for kraft paper.

1.7 Justification of Study

The useful life of oil-filled power transformers is dependent on the dryness of their kraft paper insulation during the operations. However, regardless of the moisture due to cellulose depolymerization, there is continuous moisture exchange between the Kraft paper and oil thus altering the dryness and dielectric properties of the Kraft paper in which it is immersed.

Biodegradable insulation oils have been in use in power transformers for more than a decade now, however there are very limited studies on moisture exchange characteristics between these oils kraft paper immersed in the oils [16, 24]. Therefore it is imperative that the moisture exchange characteristics between kraft paper and these vegetable-based insulation oils are explored extensively. This is more so because at low frequencies, the dielectric constant of moisture is 80; which is much higher than that of all normal constituents of kraft paper. Thus small quantity of moisture in the kraft paper has a profound effect on the dielectric constant of paper.

It is therefore relevant that the characteristics of the kraft paper immersed in the evolving vegetable-based insulation oils generally and palm-based insulation oils particularly are fully understood so as to guide power transformer designers and users alike.

1.8 Contribution of Study

The presence of moisture in the oil and kraft paper insulation of oil-filled the transformers can be catastrophic. This is because both are capable of having the moisture absorbed within it as well as exchanging it with the other; based on concentration of moisture in either and temperature gradient inside the transformer. Although moisture in either oil or paper is bad for oil-filled power transformers, the moisture in the paper determines the continuous operation of the transformer. Moisture in the paper will increase its charge density because moisture is a polar fluid and hence the paper becomes more conductive under electrical stress. Thus moisture in the oil will reduce the breakdown voltage (BDV) in the oil while moisture in the paper increases DC conductivity. Therefore, it is important to consider moisture when selecting transformer insulation.

Various factors are considered when selecting insulation oil for oil-filled power transformers. Lately, safety and environmental factors have encouraged the development and use of some vegetable insulation oils as alternatives for petroleum-based mineral insulation oils. Insulation oils like FR3, Biotemp and PFAE are already in commercial use while some like RBDPO are at various stages of development. However, unlike mineral insulation oils, these vegetable oils are hygroscopic and they have the capability to retain relatively large quantity of the moisture they absorb. Therefore there is need to understand the effect insulation oil with such high moisture content will have on the kraft paper in which the paper is immersed in.

In this research, moisture absorption characteristics of four vegetable insulation oils and how they affect the kraft paper immersed in any of the four oils are studied. The understanding of these characteristic behaviours will aid the development and use of vegetable insulation oils as power transformers liquid insulators as the relationship between kraft paper and vegetable insulation oil in terms of moisture exchange will be further understood.

1.9 Thesis Outline

This thesis has six chapters that are outlined as follows;

Chapter 1 gives a broad background introduction to transformers, their insulation system and constituents. It also identifies the problem and gives the scope and objective of this research. Furthermore the contribution of this research is highlighted.

In Chapter 2, previous published research on power transformer insulation, factors affecting its performance and methods of their assessment are presented. Special interest was given to previous research on biodegradable insulation oils and the method of kraft paper assessment in transformers.

In Chapter 3, a detail description of the samples used in this study and their preparation method is presented. Also presented are the details of equipment used, experimental design and the experimental set-ups and procedure.

In Chapter 4, the experimental results are presented and discussed. These results include the moisture absorption into the oil, the structural changes in the oil due to the absorbed moisture, wetting and absorption of kraft paper immersed in the oil and the dielectric strength of the oil and DC conductivity of the kraft paper immersed in such oils.

In Chapter 5, the result from chapter 4 were used to develop the characteristic behavior of both oil and solid insulators. Thus analogies are made based on the empirical observations made.

Finally, Chapter 6 gives the conclusion of the findings and contribution of this research. Furthermore, suggestions for future research are also presented.

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